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Maciej SPROCH
Jarosław MAMALA
Andrzej AUGUSTYNOWICZ
Mariusz GRABA

Combustion Engines
Polish Scientific Society of Combustion Engines

Research on fuel and electric energy consumption in passenger cars in a mixed cycle, using the example of local road traffic in Opole

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This paper presents a comparative analysis of fuel and electric energy consumption by passenger cars in a mixed cycle in real road conditions, taking into account the specific nature of local traffic in the city of Opole. The research was carried out in real road conditions on a designated road cycle, in accordance with the guidelines described in the RDE (Real Driving Emissions) road cycle procedure. The designated road cycle reflects the conditions prevailing on urban, rural, and motorway roads. The results obtained from the road cycle were compared with the fuel and electric energy consumption values declared by car manufacturers in the type-approval documentation authorizing the car for use on public roads. The comparative analysis revealed discrepancies between actual and laboratory data, which for electric passenger cars are determined in relation to the WLTP cycle. In the case of combustion engine passenger cars, fuel consumption was additionally converted into energy expenditure, which enabled a comparison of the energy efficiency of different drive systems in real road conditions in the TTW (Tank-To-Wheels) system. The article highlights the challenges of developing a representative road cycle for local road conditions that complies with RDE guidelines.

Key words: *RDE, WLTP, BEV, fuel consumption, energy efficiency*

1. Introduction

In recent years, there has been a rapid development of alternative propulsion technologies, in particular electric (BEV) and hybrid (HEV/PHEV) cars, with an ongoing debate as to which propulsion system will be dominant in the future. A clear increase in the number of passenger cars equipped with electric propulsion is already being observed. According to the International Energy Agency (IEA), global sales of electric passenger cars exceeded 17 million units in 2024, accounting for more than 20% of all new passenger cars put on the road. Projections for 2025 show a further increase in sales to more than 20 million electric cars, meaning that at least a quarter of all passenger cars sold globally will be electric [16]. At the same time, the issue of reliably assessing the electric energy consumption under the actual operating conditions of an electric car is becoming increasingly important [23, 33]. Many studies have been devoted to this problem and are being carried out by various research institutions, providing databases used by car manufacturers [7, 11]. Different companies and organisations have developed tests to determine the driving range of electric vehicle with different results. Some tests have been standardised where the procedure must follow specific protocols such as NEDC, WLTP, FTP-75 and JP-08 [5]. Research procedures based on modelling, simulation, and optimization of the electric vehicle powertrain are proposed, taking into account various factors affecting the vehicle's range [2]. Driving conditions, the influence of auxiliary devices, the driving style of the driver and the braking energy recuperation strategy were considered to be the most important. The driving range of an electric vehicle is therefore not a fixed value, as it depends on many factors such as driving mode [25], road type [22], environment [17], battery aging [35], etc. Therefore, the actual value is currently different from the car manufacturer's data. The driving range depends on the capacity of the battery, provided that the above-mentioned factors remain constant, so a higher capacity results in a longer range. Nevertheless, battery capacity is not constant as it evolves with discharge rate and power demand, resulting in variable autonomy and driving range. The impact of discharge rate has been extensively studied by many authors analysing various factors that modify battery capacity due to operating conditions (uncertainty in charging decisions) [37]. In 2017, the Real Driving Emissions (RDE) cycle for combustion-powered passenger cars was introduced. It was based on real road conditions. It was introduced as part of the European Union's vehicle emissions regulations [8] to measure actual emissions during normal driving on the road and not just under laboratory conditions [24, 31]. The justification for the introduction of the cycle and its further development is confirmed by studies conducted which show significantly higher emissions during on-road measurements than those reported during chassis dynamometer tests [29, 32].

Regardless of the powertrain used in a passenger car, its type-approval documentation contains information on the fuel and/or electric energy consumption per 100 km travelled. Since September 2017, new regulations have been introduced, replacing the NEDC laboratory tests with WLTP cycles for newly manufactured cars. The driving time has been changed from 20 to 30 min., the distance covered has been increased from 11 to 23.25 km and the average cycle speed has been increased from 34 to 46.5 km, while the maximum speed has been increased from 120 to 131 km/h. This change gives a more reliable reference of the cycle to road conditions, but not the actual road conditions. A turning point in considering the reliability of fuel consumption and emission data and was the so-called 'Diesel gate scandal', which revealed the use of so-called 'defeat devices' – solutions to identify the test procedure and the possibility of artificially underestimating emissions under laboratory conditions [10]. A study by Franco et al. showed that nitrogen oxide emissions under real-world driving conditions could exceed acceptable limits by up to 20 times, especially for modern diesel cars formally meeting Euro 5 and Euro 6 standards [13]. In response to a crisis of confidence in test procedures, the aforementioned Real Driving Emissions (RDE) procedure was developed to make measurements more transparent and representative [30]. On-road emissions of nitrogen oxides, hydrocarbons or carbon monoxide are very sensitive and variable, but carbon dioxide emissions resulting mainly from fuel burned show less sensitivity [1, 14, 20, 28, 35]. An important aspect of the test procedure is that there are a number of factors that affect fuel consumption and emissions [28]. These can be generally divided into weather-related factors (wind speed and direction, humidity and temperature), road topography (road grade, elevation, surface roughness), road environment (traffic condition, road features, travel distance), driving dynamics (speed, acceleration, deceleration, power demand) and driver behaviour (timid, aggressive) [15, 34, 36].

In view of taking the above into account, it is currently recognised that the RDE cycle procedure allows fuel consumption and carbon dioxide emissions to be determined in a realistic manner with the possibility of comparing them authentically with each other, with repeatable journeys over a given road cycle. As a result of the aforementioned several aspects of the problem under consideration, the question arises in the context of the changes in the segment of electric passenger cars produced and changes in the measurement procedure: How to reliably compare the fuel and electric energy consumption of the new types of propulsion systems – especially combustion-electric (hybrid) and electric – in the context of their consumption under conditions of everyday use. This issue becomes particularly relevant under local traffic conditions, where it is influenced by traffic volume, infrastructure, terrain or frequency of stops and accelerations, among other factors [3]. Many studies have found that local driving conditions, including the intensity of acceleration or frequency of stops, have a significant impact on the energy intensity of an electric car. EVs with different drivetrain types show different sensitivity to these factors, as confirmed by the study of Thomas et al. [30]. In the article, Mamala et al. found that the frequent braking and speed changes characteristic of urban driving contribute to efficient energy recovery in electric cars, increasing their energy efficiency [18, 19]. In contrast, for conventionally powered cars, driving in a similar style usually means an increase in fuel consumption. In this context, the findings of Fluder et al. are also relevant, as they demonstrated that the driving mode selected in a hybrid vehicle has a significant impact on the nature of energy flow and, consequently, on total fuel and energy consumption in the RDE test. Furthermore, these studies have shown that the energy efficiency of a vehicle varies depending on the drive control strategy, confirming the need for real-world measurements also for HEV/PHEV vehicles [12].

In light of the above, the analysis of fuel and electric energy consumption in the RDE cycle, set in the context of local driving conditions – on the example of mainly the Opole city area – is a justified and necessary approach for a full evaluation of the efficiency of the passenger car powertrains.

2. Research methodology and object of research, and justification for own research

2.1. Methodology of conducting own research

In view of the constant discrepancies between the declared and actual fuel and electric energy consumption at variable speed, the authors undertook their own research aimed at comparing the data from the tests approving the car for road traffic with the results obtained in local real traffic conditions. To this end, based on the RDE cycle guidelines, a mixed cycle road test was developed, with the route running mainly through the city of Opole and its immediate surroundings. The total length of the route was 92.5 km and included urban, rural, and motorway sections, covering both infrastructure characteristics and traffic intensity. Each of the declared road sections was at least 16 km long, and the proportion of individual traffic phases were determined for the road cycle developed in this way. For the road cycle prepared in such way, road tests of passenger cars were carried out using the individual case method, for which the unit energy consumption in the TTW system was determined.

The tests were conducted in a certain manner, ensuring the comparability of results between passenger cars and compliance with road test requirements. Each passenger car completed the test route with a single driver, while recording traction indicators of the speed profile and drive system indicators, with its mass in accordance with the RDE cycle requirements. The energy expenditure of the electric passenger car was recorded by measuring the energy consumption from the traction battery in terms of its current and voltage. For the combustion engine drive system, fuel consumption was measured from the fuel tank in the form of fuel mass loss over time. The obtained data allowed the determination of the energy consumption per unit distance (kWh/100 km) and the energy consumption per unit mass of the car (J/(kg·m) for both types of powertrains.

2.2. Description of research objects

Passenger cars representing different drive units in an automated drive system were used for the road tests. The first passenger car is a fourth-generation Škoda Citigo-e electric vehicle (BEV) manufactured in 2019 (Fig. 1). It is a compact car equipped with an electric drive powered by a lithium-ion battery pack with a net capacity of 32.3 kWh (total capacity: 36.8 kWh). The curb weight of this electric car is 1235 kg, of which 248 kg is accounted for by the traction battery installed in the chassis. The technical data of the EV are shown in Table 1.

The second passenger car is an internal combustion engine (ICE) car, an Audi Q5 manufactured in 2019, with a spark ignition (gasoline) engine with a displacement of 1984 cm^3. The car is equipped with an AWD (quattro) drive system (Fig. 2), an automatic transmission, and driver assistance systems typical for the mid-size SUV segment. The curb weight of the ICE car is 1789 kg. The technical data for the combustion engine vehicle is provided in Table 2.

Fig. 1. Test object no. 1 [27]

Table 1. Technical data of the BEV [27]

Technical data	Value
Gross battery capacity	36.8 kWh
Net battery capacity	32.3 kWh
Maximum speed	130 km/h
Average energy consumption WLTP	12.6 kWh/100 km
WLTP range	265 km
Engine power	61 kW
Torque	212 Nm
Curb weight	1235 kg

Fig. 2. Test object no. 2 [4]

Table 2. Technical data of the ICE vehicle

Technical data	Value
Engine capacity	1984 cm^3
WLTP CO_2 emission	187 g/km
Maximum speed	240 km/h
Average fuel consumption WLTP	8.3 dm^3/100km
Basic fuel range	843 km
Engine power	185 kW
Torque	370 Nm
Curb weight	1789 kg

The passenger cars used in the tests differ in terms of design, drive system, and traction characteristics. A car equipped with an electric drive system, taking into account the technical data, has a significantly lower curb weight and no gearbox compared to a car with a conventional drive system, and is a typical type of passenger car optimized for urban driving, providing a range suitable for everyday use with an automatic transmission. Differences in weight, movement resistance, type of drive, and intended use significantly affect energy consumption in real road conditions, which makes their comparison particularly interesting from the point of view of analysing unit energy consumption per 1 kg of car weight.

An important element of the measurements performed in the road cycle is the measurement system for traction indicators and the drive system. A GPS data recording device was used to record traction cars – speed, acceleration, distance travelled. For drive system indicators, a proprietary measurement system developed in LabView environment was used It enables the recording of drive system indicators in the time domain from the on-board data transmission network based on the CAN BUS, recording, among other things the rotational speed of the electric motor drive shaft, the intensity and current supplying the electric motor, torque, battery capacity, acceleration pedal, distance, electric motor power, and the power required to drive additional devices (Fig. 3).

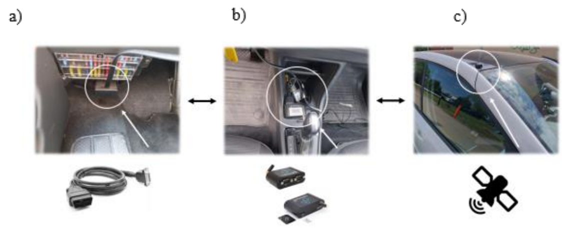

Fig. 3. Device for measuring traction indicators and the drive system: a) connection to the CAN BUS network, b) data recording device, c) GPS system recording [6]

In the case of a vehicle with a conventional internal combustion engine, fuel consumption was determined on the basis of data recorded using one of the dedicated interfaces for Volkswagen group cars (VCDS Diagnostic System). This enabled the reading and recording of the engine's operating parameters in real time. The basic parameter used in the analysis was the only signal for instantaneous fuel consumption, recorded in volume units (l/h). This data was recorded continuously during the test drive at a sampling frequency of 0.25 Hz.

In order to determine the mileage fuel consumption on a given section of the route, instantaneous fuel consumption was summed and then converted in relation to the distance travelled, which allowed for obtaining the fuel consumption unit expressed in liters per 100 km (l/100 km). The solution used is highly repeatable under comparative conditions, which makes it useful in relative analyses (e.g., comparison of routes, driving styles, or vehicles with different drive systems). The accuracy of fuel consumption measurement results from the method and algorithms applied by the vehicle's onboard computer manufacturer. The fuel measurement is based on the injector performance corrected for fuel temperature. In this case, these are Bosch injectors with a flow rate of 4 ml/s under pressure, which, with a signal sampling rate of 0.25 Hz, allows recording instantaneous fuel consumption with a dose of 1 ml.

Fuel consumption measurement for a vehicle with an internal combustion engine was an additional and comparative measurement applied in road testing. Therefore, the accuracy of fuel flow through specific injectors was not determined in relation to the gravimetric fuel consumption method. The injector calibration performed by the manufacturer, with coding specific to the engine control computer, is sufficient for road measurements based on cumulative fuel consumption and average values, while the obtained data on mileage fuel consumption should be treated as approximate.

2.3. Development of a road test in a mixed cycle

The development of a road test cycle based on the requirements of the RDE (Real Driving Emissions) procedure is a challenge when analysing the actual energy or fuel consumption in the drive system. Unlike laboratory test conditions, such as WLTP or the earlier NEDC, the RDE procedure requires measurements to be taken in real traffic conditions, taking into account variations in speed, terrain gradients, road, and weather conditions. This subsection presents the assumptions and process of developing a mixed cycle road test, which was used to compare the energy consumption of electric and combustion engine cars. The development of the test includes not only the selection of a route in accordance with RDE metrics, but also ensuring its representativeness for typical conditions of electric car use.

Table 3. Requirements for the RDE procedure compared with WLTP test conditions: a) road conditions, b) boundary conditions [9]

a)

RDE			WLTP
Test details		RDE test conditions	WLTP test conditions
Type of trip (test)		Real traffic	Laboratory test
Total trip duration		90–120 min	~30 min.
Driving area	Urban	> 16 km	Total distance: ~23.25 km
	Rural	> 16 km	
	Motorway	> 16 km	
Ratio of driving in the area to the total distance	Urban	29–44%	Specific driving phases: Low; Medium; High; Extra high
	Rural	23–43%	
	Motorway	23–43%	
Average driving speeds	Urban	15–40 km/h	Overall average: ~46.5 km/h
	Rural	60–90 km/h	
	Motorway	> 90 km/h (> 100 km/h for > 5 min)	

b)

RDE			WLTP
Parameter		RDE test conditions	WLTP test conditions
Vehicle weight		≤ 90 of max vehicle weight	Test weight – reference weight (dependent on vehicle variant)
Elevation	Moderate	0–700 m	No evaluation changes
	Extended	700–1300 m	
Altitude difference		Between start and finish of trip > 100 m	No
Cumulative altitude gain		1200 m/100 km	No hills
Ambient temperature	Moderate	0–30°C	~23°C
	Extended	(–7°C) – 0°C 30–35°C	
Percentage of stopping		6–30% during the trip in the urban area	Urban cycle simulation
Maximum speed		145 km/h (160 km/h for 3% of the driving time in the motorway area)	Up to ~131 km/h (in the 'Extra high' phase)
Dynamic boundary conditions	Max. metric	95th percentile v·a	Specific acceleration and deceleration points – no RPA
	Min. metric	RPA (Relative Positive Acceleration)	
Use of auxiliary systems		Free use without restriction as in real use	Limited

2.3.1. Detailed guidelines for RDE-compliant road cycles

To fully illustrate the difference between tests and real-world tests, a comparison of the requirements is presented in the form of Table 3 [9].

2.3.2. Detailed description of the mixed cycle in Opole

The road cycle (Fig. 4) ran mainly through the city of Opole, in accordance with the research objective. Due to the proximity of a motorway, this section of the road was integrated into the road cycle as a high-speed traffic area. The total distance of the route was in line with the RDE requirements Depending on the traffic intensity, the journey took between 90 and 120 minutes. The characteristic points of the route are shown below.

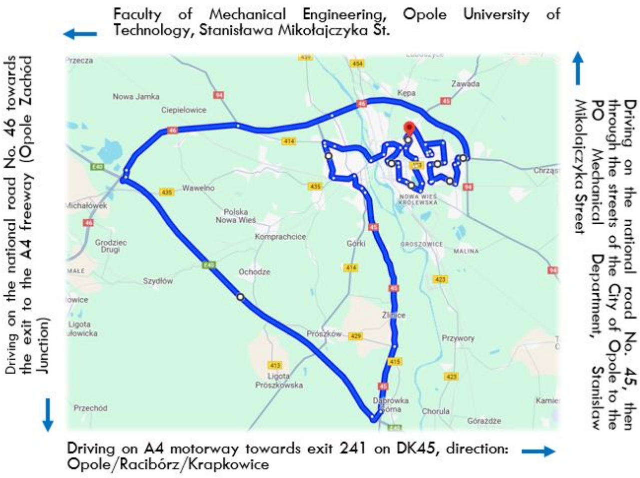

Fig. 4. Diagram of the most important points along the route

The cycle consists of five stages, including urban, rural, and motorway driving, starting and ending at the Faculty of Mechanical Engineering of the Opole University of Technology. The total distance is 92.5 km, and the estimated travel time is 1 hour and 35 minutes. The route is characterized by varied topography (143–195 m above sea level) and a speed range typical for road cycles (average 50–60 km/h, maximum 140 km/h). The most important points along the route include key transport sections around Opole, providing various traffic conditions. Taking into account the speed classification and data from the running through the city of Opole, it was possible to determine the distance for three characteristic driving areas, hence, in the urban area, the vehicle travelled 39.6 km, in the rural area 28.7 km, and 26.3 km in the motorway area, meeting the minimum distance requirement of 16 km in a given area. This route was planned to take into account real traffic conditions and topography, while meeting the RDE test requirements for distance, speed, and elevation difference.

The structure of the cycle was verified by analysing telemetry data, and the results were presented in the form of graphs and tables.

Figure 5 shows a visualization of the speed profile for the entire distance, divided into speeds that determine the area of travel: urban, rural, and motorway.

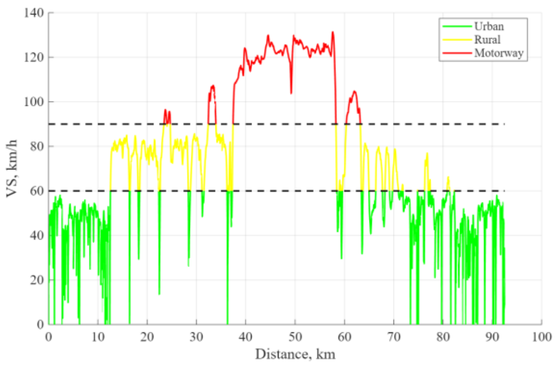

Fig. 5. Recorded speed profile for the RDE cycle in the Opole city area for a sample trip, VS – Vehicle Speed

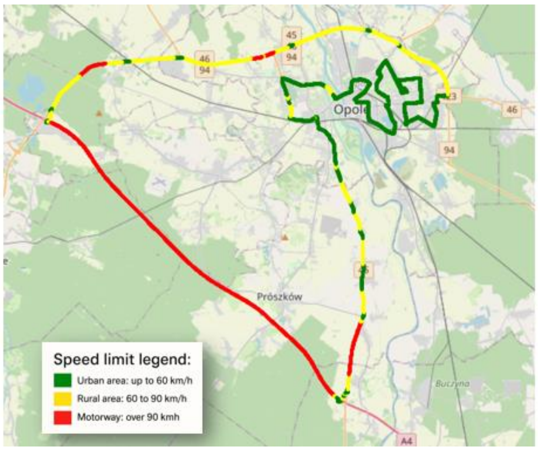

Fig. 6. Visualisation of driving speed for a recorded road cycle

Thanks to the data recorded by the GPS system, it was possible to compile the most important kinematic parameters graphically on a map (Fig. 6) and in the form of table (Table 4), comparing them with the requirements of the RDE cycle procedure.

Table 4. Comparison of measurement data with the conditions of the RDE test procedure for cycle running through the city of Opole

Parameter	Value	RDE test conditions
Route loop area	The city of Opole and the surrounding area	Variable driving area: – urban area – rural area – motorway area
Total driving time	114 min	90–120 min
Total distance	92.5 km	> 48 km
Avg driving speed – urban areas	31.0 km/h	15–40 km/h
Avg driving speed – rural areas	74.9 km/h	60–90 km/h
Avg driving speed – motorway areas	113.2 km/h 11.5 min	> 90 km/h (> 100 km/h for 5 min)
Distance in urban areas	39.6 km	> 16 km
Distance in rural areas	28.7 km	> 16 km
Distance in motorway areas	26.3 km	> 16 km
Percentage of urban areas	42.8%	29–44%
Percentage of rural areas	31%	23–43%
Percentage of motorway areas	26.1%	23–43%
Percentage of time spent stationary in urban areas	27%	6–30%

Compliance with the RDE procedure	✓

Data from the on-board GPS receiver was also used to analyse the topography of the terrain along the entire test route. Based on the recorded geographical coordinates and altitude above sea level, it was possible to reconstruct the elevation profiles of the route (Fig. 7). The altitude values were digitally processed and then converted into a time series, which made it possible to calculate the total altitude gain in accordance with the requirements of the RDE (Real Driving Emissions) metric.

Fig. 7. Height profile and data for a registered sample measurement section

Only positive altitude changes (ascents) were used for further analysis, which made it possible to assess the actual load on the drive system resulting from the terrain. The values obtained were referenced to the total length of the route, which made it possible to verify compliance with the requirement: a maximum of 1200 m of elevation gain per 100 km (i.e. 12 m/km). In the analysed case, this value was 4.9 m/km, which means that the route was within the limits acceptable for RDE tests and can be considered representative in terms of topography. The data is summarised in the Table 5.

Table 5. Summary of terrain topography data

Parameter	Value
The main area	City of Opole
Total estimated driving time	1 h 35 min.
Total distance	92.5 km
Lowest point	143 m a.s.l.
Highest point	195 m a.s.l.
Average driving speed	50–60 km/h
Maximum driving speed	140 km/h
The greatest difference in height	52 m a.s.l.
Height difference (start – finish)	~0.3 m
Total height increase	490 m/100 km

Compliance with the RDE procedure	✓

3. Results and data analysis

3.1. Presentation of actual measurement data

Table 6 shows the discrepancy between actual and declared (homologated) electric energy consumption. In the case of a car equipped with an electric drive system, during test no. 1, with active and effective energy recuperation, the average energy consumption was 11.1 kWh/100 km, which was 12% lower than the homologation value (WLTP). A similar situation occurred in the case of a combustion engine car, where fuel consumption was 22.3% lower than the declared value. In order to verify the impact of the energy recovery level, a test with a minimum level of recuperation was carried out in test no. 2. In this case, the energy consumption was 13.2 kWh/100 km, which is only 4.8% higher than the WLTP value (12.6 kWh/100 km). Setting the control preferences in the drive system by the intensity of energy recuperation has a significant impact on the total energy consumption in the actual driving cycle.

Table 6. Comparison of actual and measured data: a) for a BEV, b) for an ICE vehicle

a)

BEV	Average EC WLTP [kWh/100 km]	Average EC RDE [kWh/100 km]
Test no. 1	12.6	11.1
Test no. 2	12.6	13.2

b)

ICE	Average FC WLTP [dm^3/100 km]	Average FC RDE [dm^3/100 km]
Test no. 3	8.3	6.8

3.2. Conversion of fuel consumption into energy expenditure

In order to compare the energy efficiency of both drive systems based on the actual road cycle, fuel consumption was converted into energy value (Wh/km), assuming the calorific value of 95-octane gasoline to be 32 MJ/dm^3 [21]. This approach allows for a direct comparison of energy values between ICE and BEV cars, also in the context of different levels of recuperation (maximum and minimum) used in electric vehicles. The results obtained are presented in a numerical summary – separately for sample drive trip.

Energy expenditure calculations for an ICE car in a TTW (Thank To Wheels) system:

$$\mathrm{E_c}\left[\frac{\mathrm{Wh}}{\mathrm{km}}\right] = \frac{\mathrm{F_c}[\frac{\mathrm{dm^3}}{\mathrm{100\,km}}]\cdot \mathrm{HV_f}[\frac{\mathrm{MJ}}{\mathrm{dm^3}}]}{100} \tag{1}$$

where: E_c – energy consumption [Wh/km], F_c – fuel consumption [dm^3/100 km], HV_f – heating value of fuel [MJ/dm^3]

$$\mathrm{E_c}\left[\frac{\mathrm{Wh}}{\mathrm{km}}\right] = \frac{6.8\left[\frac{\mathrm{dm^3}}{\mathrm{100\,km}}\right]\cdot 32\left[\frac{\mathrm{MJ}}{\mathrm{dm^3}}\right]}{100} \tag{2}$$

Energy expenditure assuming that 1 MJ = 277.78 Wh:

$$\mathrm{E_c}\left[\frac{\mathrm{Wh}}{\mathrm{km}}\right] = 604.4\,[\frac{\mathrm{Wh}}{\mathrm{km}}] \tag{3}$$

This value is the chemical energy value of the fuel type used (Table 7).

Table 7. Summary of energy expenditure for an ICE car

ICE	Average FC RDE [dm^3/100 km]	ETTW [Wh/ km]
Test no. 3	6.8	604.4

Table 8. Summary of energy expenditure for a BEV car

BEV	Average EC RDE [kWh/100 km]	ETTW [Wh/km]
Test no. 1	11.1	111
Test no.2	13.2	132

However, the energy expenditure values for a BE vehicle in the TTW (Thank To Wheels) system can be calculated by taking into account the average energy consumption calculated on the basis of the voltage and current recordings of the vehicle's traction battery. The results are presented for two tests carried out and are shown in Table 8.

In road tests based on the RDE procedure, the energy consumption of a combustion engine (ICE) car was 604.4 Wh/km (TTW) and was calculated based on fuel consumption in a full road cycle. For an electric vehicle (BEV), varying values of electric energy consumption were recorded, amounting to 111 Wh/km for test no. 1, with maximum recuperation settings, and 132 Wh/km for test no. 2, with minimum energy recuperation. The electric car showed lower energy consumption in the TTW system compared to the ICE, more than 5 times lower, depending on the intensity of recuperation. Effective recuperation (test no. 1) additionally reduced energy consumption by approximately. 15.9% compared to test no. 2.

3.3. Energy efficiency analysis for specific driving areas

The recording of traction and drive system indicators made it possible to analyse the impact of actual road conditions on energy efficiency for specific driving areas, in accordance with the adopted RDE procedure classification, i.e., urban, rural, and motorway areas. In order to present the energy consumption of the drive system, the results were converted into kWh and kWh/100 km (Table 9). The weights for individual driving areas are also given in brackets, referring to the total energy and total distance travelled, respectively [26].

Table 9. Summary of energy expenditure for individual driving areas: a) BEV with maximum recuperation, b) BEV with minimum recuperation, c) ICE vehicle in normal operating mode [26]

a)

BEV	Driving area	ETTW [kWh]	Distance [km]	Specific EC [kWh/100 km]
Test no.1	Urban	3.4 (32.6%)	39.2 (42.4%)	8.57
	Rural	3.2 (31.3%)	30.2 (32.6%)	10.7
	Motorway	3.7 (36.1%)	23.1 (25.0%)	16.1

b)

BEV	Driving area	E_{TTW} [kWh]	Distance [km]	Specific EC [kWh/100 km]
Test no.2	Urban	3.8 (31.5%)	38.4 (41.5%)	10.0
	Rural	3.3 (31.3%)	27.7 (29.7%)	11.9
	Motorway	5.1 (41.6%)	26.4 (28.5%)	19.3

c)

ICE	Driving area	E_{TTW} [kWh]	Distance [km]	Specific EC [kWh/100 km]
Test no.3	Urban	22.6 (40.4%)	36.2 (39.1%)	62.4
	Rural	15.0 (26.8%)	29.6 (32.0%)	50.8
	Motorway	18.3 (32.7%)	26.7 (26.4%)	68.5

In accordance with the adopted classification of RDE cycle areas (urban, rural, motorway), it showed significant differences in specific energy consumption (kWh/100 km) and in the structure of the share of individual areas in total energy consumption. For a BEV car driving with maximum recuperation, the lowest energy consumption occurred in the urban area – 8.57 kWh/100 km, with a high distance share (42.4%) and a correspondingly lower energy share (32.6%). On motorways, electric energy consumption al-most doubled to 16.1 kWh/100 km. Although motorways accounted for only 25% of the route, they consumed as much as 36.1% of the total energy, due to strong aerodynamic resistance at higher speeds.

In the case of the RDE cycle with the same car but a different energy recovery configuration (minimum electric energy recovery), the reduction in recovery resulted in an increase in unit electric energy consumption in each area, especially in urban and motorway areas: urban: 10 kWh/100 km, motorway: 19.3 kWh/100 km. In this case, the motorway area, despite accounting for 28.5% of the route, already accounted for 41.6% of total energy consumption, which further highlights its energy intensity in the absence of electric energy recovery.

RDE testing with a car with a conventional internal combustion engine (ICE) in urban areas, despite accounting for only 39.1% of the distance, accounted for as much as 40.4% of the total energy consumption, with a mileage electric energy consumption of as much as 62.4 kWh/100 km, which indicates very low efficiency in starting and braking conditions in the TTW system. The highest electric energy consumption per kilometre was recorded on the motorway – 68.5 kWh/100 km, and the share of this area in the distance was the smallest (26.4%).

3.4. Specific energy consumption

In order to carry out a physically comparable analysis of the energy efficiency of cars, a unit energy consumption indicator was used, which determines the amount of energy consumed to move a given car mass over a specific distance, regardless of the type of drive or fuel. Unlike commonly used indicators such as fuel consumption (dm^3/100 km) or electric energy consumption (Wh/km), the unit J/(kg·m) is based solely on the basic SI units (mass, distance, energy), thus ensuring full comparability of results between cars of different mass, design, and power source.

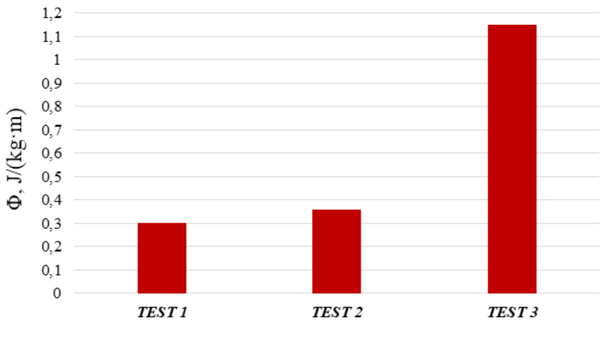

Fig. 8. Specific energy consumption for the BEV and ICE vehicle

For the calculations for the two cars tested, the masses before the road cycle test, including the driver's weight, were used. For the BEV car, this value was 1335 kg, while for the ICE car it was 1889 kg. The results are summarised in the Fig. 8.

The electric passenger car (BEV) demonstrated significantly lower specific energy consumption per unit of mass and distance travelled. During the first run, with maximum energy recovery, the specific energy consumption was 0.30 J/(kg·m), which was 74% lower in comparison to the ICE car (Φ = 1.15 J/(kg·m)). During the second run, with minimum energy recovery, the Φ value increased to 0.36 J/(kg·m), but was still 68% lower than the value obtained by a conventional car.

4. Conclusion

Analysis of actual data from the RDE cycle clearly indicates a significant advantage of electric vehicles (BEVs) over internal combustion engine vehicles (ICEs) in terms of energy efficiency – both in the TTW (Tank-to-Wheel) system and in terms of physical energy consumption [J/(kg·m)]. The lowest unit energy expenditure was achieved by the BEV car using the maximum level of energy recuperation (0.30 J/(kg·m)), while the highest was achieved by the ICE car (1.15 J/(kg·m)), which confirms the approximately four times higher unit energy consumption of a conventionally powered car. Even under conditions of limited recuperation (test no. 2), the electric car retains more than three times higher efficiency per unit of mass and distance travelled. Empirical data recorded during road tests also showed a significant impact of environmental characteristics and traffic dynamics on the distribution of energy consumption in different driving areas. In the case of BEVs, the highest energy consumption occurred in motorway conditions, while for ICEs it occurred in urban environments. This is due to differences in the traction characteristics of the car and its energy loss mechanisms, especially aerodynamic losses and rolling resistance (dominant in motorway traffic), as well as the lack of recuperation and the low efficiency of the combustion engine during frequent starting and stopping (typical of urban traffic). Currently, there is no strict standardisation of the mixed driving cycle for local conditions, which limits the possibility of objectively comparing cars in a given traffic environment. The use of averaged homologation standards (e.g. WLTP) does not take into account the characteristics of local traffic, the intensity of intersections, the length of stop phases, or the typical speed profile, which can lead to significant deviations in actual energy and emission results. Therefore, the development and validation of a local mixed driving cycle that reflects the real conditions of driving on the streets of Opole and its surroundings is an important direction for further research and may contribute to a more accurate assessment of drive technologies and the planning of future sustainable urban mobility strategies.

Nomenclature

AWD	all-wheel drive
BEV	battery electric vehicle
CAN	controller area network
CO	carbon monoxide
DK	national road
E_c	energy consumption
F_c	fuel consumption
EV	electric vehicle
HC	hydrocarbon
HEV	hybrid electric vehicle

HV_f heating value of fuel
ICE internal combustion engine
NEDC New European Driving Cycle
NO_x nitrogen oxides
PHEV plug-in hybrid electric vehicle
RDE real driving emissions
SUV sport utility vehicle
TTW thank to wheels
WLTP Worldwide Harmonized Light Vehicle Test Procedure

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Maciej Sproch, MEng. – Faculty of Mechanical Engineering, Opole University of Technology, Poland.
e-mail: *m.sproch@student.po.edu.pl*

Prof. Jarosław Mamala, DSc., DEng. – Faculty of Mechanical Engineering, Opole University of Technology, Poland.
e-mail: *j.mamala@po.edu.pl*

Prof. Andrzej Augustynowicz, DSc., DEng. – Faculty of Mechanical Engineering, Opole University of Technology, Poland.
e-mail: *a.augustynowicz@po.edu.pl*

Mariusz Graba, DEng. – Faculty of Mechanical Engineering, Opole University of Technology, Poland.
e-mail: *m.graba@po.edu.pl*